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Temporal Probabilistic Constellation Shaping for WDM Optical Communication Systems

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Abstract *Finite state machine sources transmitting QPSK are studied as input to WDM optical fiber systems with ideal distributed Raman amplification. The probabilities of successive constellation symbols are shaped for nonlinear transmission and gains of around 500km (5-10%) are demonstrated.*

Introduction

Nonlinear interference (NLI) is currently one of the major factors limiting the reach of wavelength division multiplexed (WDM) optical fiber systems. Furthermore, the NLI introduces memory in the channel, which makes the information theoretic analysis into channel capacity and achievable information rates (AIR)s difficult. The standard approach for estimating AIRs is to employ the split-step Fourier method (SSFM) for solving the Manakov equation for fiber propagation[1]. The result is usually an AIR estimate, which decreases with launch power after a certain optimal point for a fixed distance due to the dominant nonlinear effects. Recently, the concept of probabilistic shaping has been investigated[2,3] for increasing the AIR of fiber links. These techniques usually operate on a memoryless assumption and their gains are therefore limited to within the linear region of transmission, or at best - the weakly-nonlinear region, where the channel can also be considered memoryless. In such cases, large modulation formats are required for achieving significant shaping gain, e.g. 64-quadrature amplitude modulation (QAM), which is difficult for implementation in transceivers with limited processing capabilities. The memory in the optical channel can be taken into account by using a finite state machine (FSM) approach at the receiver[4], which allows for increased AIRs by using the BCJR algorithm for estimating the mutual information (MI) between the input and output sequences of a certain length, generally longer than 1.

In this paper, a finite state machine source (FSMS) is considered as input to the fiber optic channel. A FSM model is also adopted for the fiber channel, which allows for computing of MI with memory, but also for optimizing the transition probabilities of the FSMS. This optimization results in improved performance particularly in the highly-nonlinear region of transmission.

Probabilistic optimization of FSMS

As mentioned, the nonlinearities introduce memory in the channel, or dependencies between the received symbols in time. The idea behind using FSMSs is to introduce dependencies between the transmitted symbols, thereby suppressing (assigning lower probabilities to) sequences, which result in strong NLI and poor performance. We refer to this process as *temporal probabilistic shaping* (TPS). TPS allows for optimizing the input for channels with memory, which for the optical channel can be much more effective than simply optimizing the probability mass function (PMF) of the constellation under the constraint of independent, identically distributed (i.i.d.) symbols in the transmit sequence. TPS was studied previously[7] with the target of ensuring a constant amplitude multi-dimensional input, however, no design rules were described for how to achieve the shaping gain in practice.

In this work, an FSMS is constructed by defining the state at time k to be the previous N transmitted symbols, $s_k \triangleq (x_{k-N}, x_{k-N+1} \dots x_{k-1})$, where N is the order of the FSMS. The current transmitted symbol x_k governs the state transition. Optimizing the stationary distribution of the transition probabilities can be done for e.g. linear impulse response channels by the generalized Blahut-Arimoto algorithm (GBAA)[5].

The GBAA is applied in this work with a few modifications. The algorithm requires knowledge of the likelihoods $p(y_k|s_{k-N}^k, x_k)$, where y_k is the received symbol at time k, and s_{k-N}^k is the state sequence from time $k-N$ to k. Since the likelihoods are not available in closed form for the optical channel, we model them as Gaussians for each possible state transition ($|\mathcal{X}|^{N+1}$ transitions in total, where $\mathcal{X}$ is the set of symbols in the con-

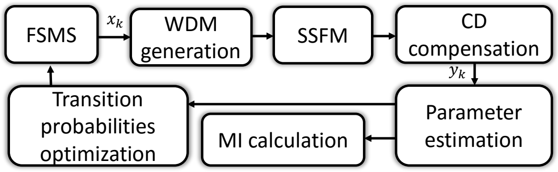

Fig. 1: Optimization process for the FSMS.

stellation, e.g. $|\mathcal{X}| = 16$ for 16QAM). The parameters of these Gaussians are estimated from training data.

The optimization process is given in Fig. 1. The FSMS is initialized with uniform transition probabilities, and thereby uniform and independent probabilities of the constellation symbols. A long sequence is generated by the source for each polarization and WDM channel separately, which are then combined and passed through the fiber via the SSFM. A standard, single mode fiber is assumed with a loss of $\alpha = 0.2dB/km$, dispersion $D = 17ps/(nm \cdot km)$ and nonlinear coefficient $\gamma = 1.3(W \cdot km)^{-1}$. A square root raised cosine filter is applied with roll-off factor 0.01, and the guardband between channels is set to 2 GHz. Ideal distributed Raman amplification is assumed.

At the receiver, the central channel is acquired and chromatic dispersion is performed in the frequency domain. The parameters of the likelihoods are then estimated, and the MI is maximized w.r.t. the transition probabilities $p(s_k|s_{k-1})$ of each state. The MI is then calculated separately[6], and the process is repeated with the updated FSMS until convergence or a certain predefined number of iterations. We note that the channel, i.e. the likelihoods, depend strongly on the input itself. The process is therefore not guaranteed to converge. However, in our simulations, convergence was usually observed before the 10-th iteration. We note that the optimization is performed in one polarization only due to the increased complexity of joint processing.

While the MI calculation and the MI optimization require similar processing steps (a BCJR algorithm is used for both), the memory M assumed for MI calculation is not necessarily the same as the order of the FSMS N. Longer M is always beneficial, however, the complexity of the BCJR is linear with the number of transitions in the receiver trellis, which is exponential with M. We note that if a receiver is to be built for such models, the same complexity is generally required for demodulation. Operating a system with highly specialized FSMS of high order which can be detected by a low-complexity trellis is therefore of interest.

Results

We demonstrate the benefits of the method for QPSK input constellation, which is chosen due to its small complexity and implementation penalty. While probabilistic shaping gain with the i.i.d. symbol assumption is not possible with QPSK due to the constant amplitude, the gains from TPS are of interest in this paper. We measure the received MI in bits per symbol per polarization (bits/symbol for simplicity), as calculated by a BCJR processing assuming M symbols of memory. The MI in this case also represents AIR. We also estimate the received *effective* SNR as $SNR = 10 \cdot \log_{10} \frac{\mathrm{E}_k\left[|x_x|^2\right]}{\mathrm{E}_k[|x_k - y_k|^2]}$, where $\mathrm{E}_k\left[\cdot\right]$ is the expectation w.r.t. k. The SNR thus includes the NLI noise.

We start by analyzing the potential benefits of optimized FSMSs as channel input in the highly non-linear region of transmission. To that end, 200 km single channel, single polarization transmission at 10 GBaud is simulated. We keep the distance short so that the major impairment is the NLI.

In Fig. 2(a), the MI is given as a function of the launch power for FSMS order of up to 3. We see increasing gains with the order of up to 0.25 bits/ symbol at the highest launch power. Fig. 2(b) shows the received SNR for each N. We see that not only the MI is increased, but also the effective SNR at the receiver side. The reason is that sequences, resulting in severe NLI are suppressed by the FSMS. The impact of the increased SNR can be seen in Fig. 2(c), where the MI is given for different values of the memory M. When independent, uniformly distributed QPSK symbols are input to the channel, processing with memory 3 provides around 0.1 bits/symbol of gain. When the FSMS state transition probabilities are optimized, the gain is increased to the above mentioned 0.25 bits/symbol. The same gain is achieved with *memoryless* processing at the receiver with complexity which is orders of magnitude smaller than that of the BCJR, at the cost of negligible complexity increase at the transmitter.

In Fig. 3, the optimized PMF of the states in the FSMS is given at the highest considered launch power $P_{in} = 7$ dBm. The state is represented by the previous two QPSK symbols (the QPSK symbol numbering is also given). We see that the optimization process favors states with close neighbors, and suppresses states, for which the two symbols are at longer Euclidean distance. The rest of the states have rather similar optimized

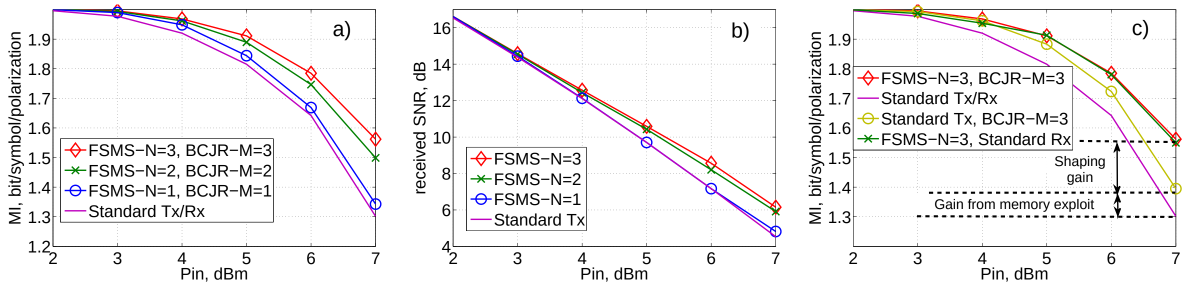

Fig. 2: Performance of FSMS in the highly nonlinear region of transmission of single channel 200 km link. a): MI comparison of different FSMS order N; b): received effective SNR for different N. Higher order FSMS result in increased effective SNR; c): Analysis of TPS gain and the gain, coming from processing of the channel memory. The shaping gain is achieved by memoryless processing ($M = 0$) due to the increased effective SNR with higher order FSMS.

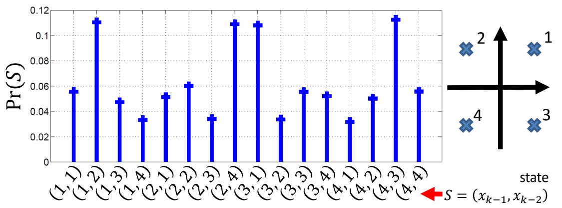

Fig. 3: Optimized stationary PMF of the states in the FSMS with $N = 2$ and single channel QPSK at $P_{in} = 7$ dBm. The state is represented by the previous 2 transmitted symbols. The numbering of the QPSK symbols is given on the right.

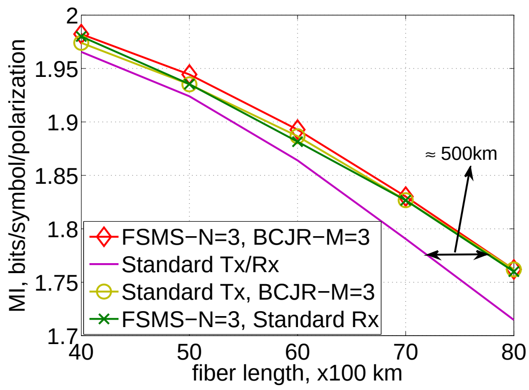

Fig. 4: Distance study of FSMS input to a WDM optical fiber with 21x100 GBaud channels. Up to 500 km gains are achieved with TPS without the necessity of BCJR processing.

probabilities of occurrence.

Finally, we study a 21x100 GBaud dual polarization WDM channel at long-haul distances. In Fig. 4, the MI at the optimal launch power is given as a function of the distance for the same transceiver configurations as in Fig. 2(c). As before, the shaping gain is achieved by memoryless processing at the receiver, which reduces the complexity significantly w.r.t. a BCJR with $M = 3$ for the same performance. At 7000 km, around 500km of gain can be achieved by shaping the transition probabilities of the FSMS.

In this work, only QPSK symbols are considered due to the exponential complexity of the full-blown receiver processing and optimization. However, as we saw, it is not always necessary. Exploiting this benefit with higher-order constellations, such as 16QAM and 64QAM may provide even higher gains at negligible complexity increase. Furthermore, as we saw in Fig. 3, the optimized state PMF has a symmetric structure. Generalizing this symmetry and imposing it on the optimization process will improve the accuracy and speed of the optimization, which is especially relevant for high-order constellations.

Conclusions

In this paper, the transition probabilities of a finite state machine source (FSMS) were optimized for nonlinear WDM transmission. We demonstrated that the resulting temporal probabilistic shaping gains can be achieved with minimal receiver effort by shifting complexity to the transmitter side. Up to 500 km of reach increase were achieved with a FSMS of third order with standard receiver processing and QPSK input for a long-haul WDM system.

Acknowledgements

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